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Testing tyres of mobile forest machines in the soil testing canal

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Abstract: The article focuses on the research of tyre rolling resistances in the soil test channel environment. The specific monitored tyre was a Mitas TS05 10.0/75-15.3 10PR diagonal tyre with an arrow tread. The measurement itself was divided into two stages. In the first stage, measurements of rolling resistance were performed on a solid concrete base of the laboratory in order to determine the internal component of rolling resistance of the tyre. In the second stage, rolling resistances were monitored on forest soil deposited in the main body of the soil channel. The mentioned measurements of rolling resistance can be considered key for further evaluation of traction and energy properties of tyres. Despite some complications which occurred during the measurement, the results obtained indicate the conclusions reached by other researchers in the field. The main conclusion of this research is to confirm the justification of using the correct or optimal level of inflation pressures of tyres of mobile energy means depending on the properties of the surfaces on which they move in order to reduce not only their energy intensity but also greater environmental acceptability.

Keywords: mobile working machine; rolling-resistance force; tensile force; tensile test; wheel bogie

The main component of the loss resistance of vehicles and mobile work machines with a wheeled chassis in agriculture and forestry is rolling resistance. If we look at universal mobile energy means such as, e.g. tractors, part of their movement takes place on paved surfaces (e.g. concrete or asphalt) and part of their work activities take place on the soil – in the field or in the forest. It is understood that if we want to minimise the rolling resistances of these mechanisation means, it will be necessary to use different tyre inflation pressures on paved surfaces than in the terrain or in the field with the unchanged construction of the used tyre casings designed by the machine manufacturer. This is, to a large extent, an advantage compared to tracked vehicles, where the resulting contact pressure on the soil depends only on the used construction of the mobile mechanism (Zemánek and Neruda 2021). Changing the tyre inflation pressure is easier to perform than completely changing the machine's tyres when the soil or road mode change.

Rolling resistance can be divided into two components. The first is the so-called internal rolling resistance, which is directly related to the deformation of the tyre casing. It is dominant especially on paved rigid surfaces, where we can neglect the deformation of the substrate itself. The second component is the external resistance, which is formed by the deformation of the substrate on which the tyre rolls. The resulting value of the rolling resistance is then given by the sum of said partial components. Rolling resistance could be defined as the energy loss caused by the rolling of a tyre caused by its imperfectly elastic deformation as well as the springing of the tyre (Pouget et al. 2012). However, as can be seen from the above, the rolling resistance of a tyre moving on a flexible surface is also caused by the deforma-

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tion of this surface itself. During movement, the tyre is deformed by vertical (radial), circumferential and lateral forces (Malaga-Toboła et al. 2019). When the tyre is loaded with a vertical force (the weight of the vehicle), the part of the curve of the running surface of the tyre (tread) which comes into contact with the road surface must be compressed to a certain length. After the tyre rotation, load on the said part of the running surface is relieved, so that the part of the rubber which was previously compressed will expand again. In a similar way, the running surface deforms in the transverse direction. After relieving the load, the rubber particles expand again. Thus, in the circumferential and transverse directions, the tyre particles alternately compress and expand at a certain frequency, which depends on the speed of the wheel, and, thus, also on the speed of the vehicle or machine (Faraji et al. 2010). The deformation energy, which is formed by the action of the mentioned vertical, circumferential and lateral forces, will not return completely after the tyre is relieved of the load. Part of the energy is used for overcoming the hysteresis losses of the tyre. According to Luchini and Popio (2007), the cause is the imperfect flexibility of the tyre, which does not return completely to its initial state due to its own damping after relieving of the load. The internal resistance of rolling friction is related to the mentioned energy for overcoming tyre losses. Part of this rolling friction component also includes the partial slip of the tread figures in the contact surface and the losses associated with the adhesion and detachment of the tread figures from the road surface (Findura et al. 2018).

A wheel moving on the soil has two effects on the soil. On the one hand, it is the contact pressure in the contact surface, which is perpendicular to the soil surface and, in the case of the drive wheel, also the shear stress, which is parallel to the soil surface. Both of these stress components cause the resulting soil tension in the area under the tyre. The contact pressure is essentially the tension between the wheel and the soil and its actual distribution under the wheel is uneven. Its maximum values can even reach twice the mean value of the contact pressure (e.g. plastic soil saturated with water), while Grečenko (1978) came to the conclusion that their mutual ratio (maximum value of the contact pressure divided by the mean value of the contact pressure) depends on the tyre inflation pressure. The mean value of the contact pressure of the tyre also depends on the actual soil properties. The mechanical properties of the soil are influenced not only by the soil compression factor, but especially by the soil moisture. The mean contact pressure subsequently affects the depth of engagement of the tyre and, thus, also the size of the outer component of the rolling resistance, which is given by the deformation of the soil surface. In this way, we could simply explain the formation of the external component of the rolling resistance, which is directly related to the deformation of the soil surface.

In the presented work, we focused on the research of the rolling resistances of a selected tyre. As a test device, we used a soil test channel, which was implemented at our workplace. The monitored tyre was a Mitas TS05 10.0/75-15.3 10PR diagonal tyre with an arrow tread. We divided the experimental measurement into two stages. In the first stage, we focused on measuring the external component of the rolling resistance of the monitored tyre on the concrete surface of the laboratory and, in the second stage, we performed measurements on a forest soil in the main body of the soil channel. Our objective was to confirm the validity of the statement that the correct or optimal choice of tyre inflation pressures can reduce the rolling resistance of wheeled vehicles and, thus, ensure greater energy savings required for their operation.

MATERIAL AND METHODS

The rolling-resistance force is one of the most important parameters of tested tyres. It is an initial point for further tyre testing in the field of traction properties and it significantly influences the energy consumption. Because of these reasons, the initial measurements in the soil testing canal were focused on the observation of this parameter. As an example, the part measured for a diagonal tyre Mitas TS05 10.0/75-15.3 10PR is shown. Its basic technical parameters, according to values given by the producer of the tyre, are shown in Table 1.

Table 1. Basic technical parameters of the tyre marked as Mitas TS05 10.0/75-15.3 10PR

Parameter	Value
Diameter of a tyre casing (mm)	800
Width of a tyre casing (mm)	277
Maximum carrying load of a non-driven tyre (kg)	1 500
Maximum carrying load of a driven tyre (kg)	1 090
Maximum inflation pressure of a tyre (kPa)	400
Weight of a tyre casing with a tyre disc (kg)	38.3

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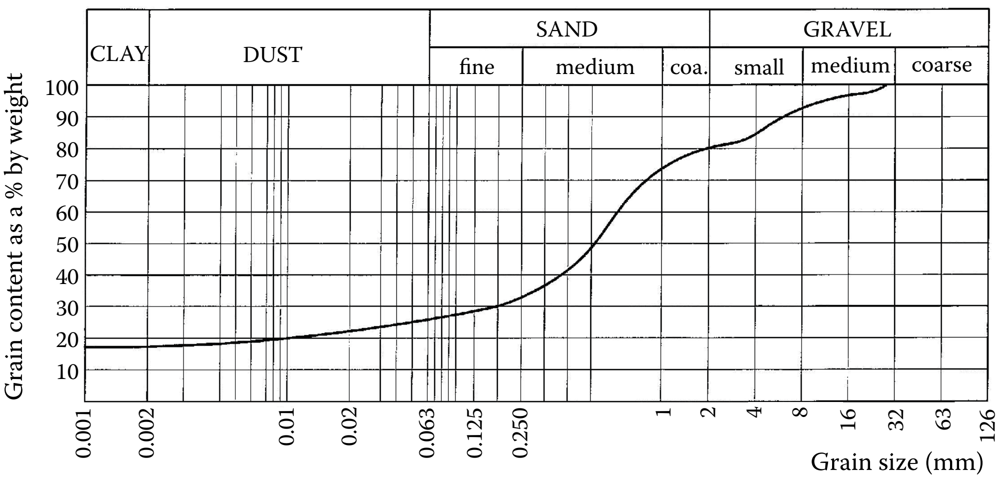
The measurement of the rolling resistance forces was conducted on the concrete surface at the beginning to obtain the internal parts of the tyre's rolling resistance forces. The construction of the soil testing canal was disassembled in this case. After that, a measurement on the soil in the soil testing canal occurred. The forest soil used in the soil testing canal was brought from the forest area focused on beech cultivation. The soil was dry and non-coherent. The soil moisture was about 3% of the relative moisture. The soil density was defined by measurement of the soil samples and, on average, was about 1 033.55 kg·m^{-3}. It is necessary to say that the soil was placed in laboratory conditions where it dried. The air temperature in the laboratory was in the range of 18 °C to 20 °C depending on the season. The granulometric analysis of the used soil was also performed by the sieving method (coarse fractions up to 2 mm) as well as by the sedimentation method (fractions smaller than 0.05 mm). From the obtained results, a grain size curve was constructed, which is shown in Figure 1. Based on the performed granulometric analysis, we can mark the used soil as a sandy clay that is slightly gravelly.

The methodology for measuring the rolling resistance of the tyre in question was simple and essentially based on pulling the main frame with the tyre by means of a braking and winding device. We used an HBM S9M/10 kN force sensor with a nominal size of 10 kN to measure the magnitude of the tensile force. The signal from the sensor was then recorded by the HBM Quantum X MX 840A measuring control panel, which is controlled by a computer with HBM Catman Easy software. This enables the subsequent conversion of the recorded files into MS Excel, in which we also evaluated the measurement results. The towing speed of the tyre due to the cramped conditions and the dimensions of the side guide of the guiding frame was at the level of 0.1 m·s^{-1}.

The measurement was undertaken at inflation tyre pressures of 100 kPa, 150 kPa, 200 kPa, 250 kPa and 300 kPa. The vertical tyre loading was undertaken at five levels: 222 kg (weight of the main frame without a tyre drive mechanism and loads), 350 kg, 478 kg, 606 kg and 734 kg. To load the tyre, mechanical loads made of steel plates with a weight of 32 kg each were used. It was decided that loading with the maximum values was not going to be performed, but the behaviour of the whole device during the gradual loading, from stability and drive points of view, was observed.

In the device, the system for the wheel drive was disassembled because of the maximum throwing-off the tested tyre. The main frame of the wheel was returned to the starting position via a supporting coiler with a performance of 1.5 kW placed on the other side of the soil testing canal. The inflation tyre pressure and vertical tyre loading were chosen to suit the technical requirements given by the tyre producer and overloading, which decreases the lifetime, was not necessary.

The measured pulling force consists of the rolling resistance force and other resistance forces which shall be accepted in the final calculation (Figure 2) in this designed way of measurement for rolling resistance of tyres.



Percentage of fractions:

clay:	17.29%	sand:	54.50%
dust:	8.50%	gravel:	19.71%

Figure 1. Grain size curve of the used soil

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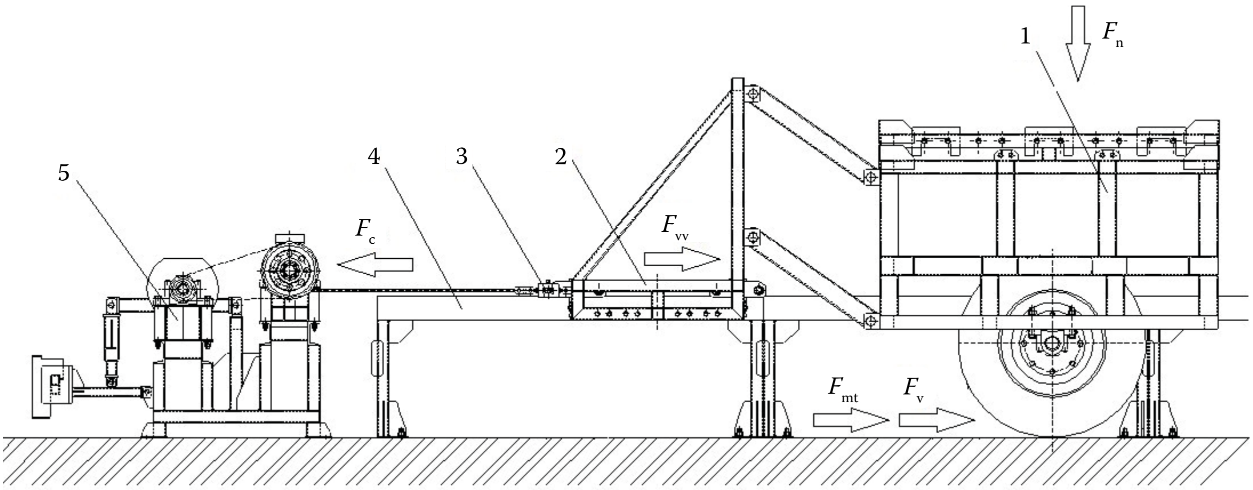

Figure 2. Force acting on the pulling of the tyre wheel (measurement on the concrete surface)

1 – main frame with a wheel; 2 – directional control frame; 3 – force sensor HBM S9M/10kN; 4 – side directional control; 5 – braking and coiling device; F_c – total tensile resistance force; F_n – normal force acting on the tyre; F_v – rolling resistance; F_{mt} – frictional resistance force in the bearings; F_{vv} – resistance force in the directional control frame

The valid Equation (1) for the total measured resistance force according to Figure 2:

$$F_c = F_v + F_{vv} + F_{mt} \tag{1}$$

where: F_v – rolling resistance force detected on the concrete surface (N); F_{vv} – resistance force in the directional control frame (N); F_{mt} – frictional resistance force in the bearings (N).

Then, it is possible to define the value of the rolling resistance force from Equation (1) as follows:

$$F_v = F_c - F_{vv} - F_{mt} \tag{2}$$

The frictional resistance force in the directional control frame was defined on the basis of free pulling of the directional control frame without connecting the main fame to the wheel. This measurement was conducted before the measurement of the rolling resistance forces of the tyres using the measuring apparatus described above.

The frictional resistance torque in the bearings of the wheel shaft is as follows:

$$M_{mt} = \mu \times P \times \frac{d}{2} \tag{3}$$

where: μ – coefficient of friction in the bearings (–); P – equivalent dynamic bearing loading (N); d – diameter of the shaft in the place of the bearing positioning (m).

The disadvantage of the equation mentioned above is that it is only correct for bearing loading at the size of $P = 0.1 \times C$, where C is a basic bearing dynamic carry capacity. In many cases, the force was overtaken. In the case of the option for the frictional coefficient in bearings, for the chosen type of bearings and the chosen way of lubrication (lubrication with a plastic lubricant), it is recommended to calculate with the value of μ = 0.001 by Brónček et al. (2015). The frictional resistance force in the bearings is calculated as follows:

$$F_{mt} = \frac{M_{mt}}{R} \tag{4}$$

where: R – rolling radius of a wheel tyre (m).

The radial reactions of the bearings placed on the shaft of the wheel were not measured. Only the force scheme and dimensions for the placement of the bearings on the shaft were counted. It means that from the known value of the vertical wheel loading, the reaction of the bearings and defined equivalent bearing dynamic loading was calculated. According to calculated results, the force value was very low which was about 1.5 N at the designed range of the vertical wheel loading. The bearing housing for the wheel placement is not equipped with contact sealing to decrease the resistance. It means that the friction is only in the bearings.

Because of the low resistance value, ignoring this type of resistance was considered. The way of cal-

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culating the pulling resistance force (in this case, it is the rolling resistance force of the wheel) is then simplified and faster.

A value of the rolling resistance force coefficient is calculated as follows:

$$f_v = \frac{F_v}{F_n} \tag{5}$$

where: F_n – normal (vertil) loading of the tyre (N).

Effective value of the rolling resistance force (outer part of the rolling resistance force referring to the deformation of the soil surface) is defined as follows:

$$F_{vep} = F_{ve} - F_v \tag{6}$$

where: F_{ve} – rolling resistance force detected on the soil (N); F_v – rolling resistance force detected on the concrete surface (N).

Effective value of the coefficient for the rolling resistance force on the soil is defined as follows:

$$f_{vep} = \frac{F_{vep}}{F_N} \tag{7}$$

The methodology for defining the effective part of the rolling resistance force referring to deformation of the soil surface (outer part of the rolling resistance force) is recommended by professor Grečenko (1978) in his work.

RESULTS AND DISCUSSION

The measurement was conducted in two stages. At first, the rolling resistance force of the tyre on the concrete surface with the disassembled wheel drive was measured. In this way, the values of the internal part of the rolling resistance force were obtained. Then, the body was mounted on the soil testing canal; it was fulfilled with soil and the measurements for the rolling resistance forces on the soil surface were conducted. The measurements were performed with five different levels of inflation tyre pressures, specifically 100 kPa, 150 kPa, 200 kPa, 250 kPa and 300 kPa and five different levels of vertical tyre loadings (222 kg, 350 kg, 478 kg, 606 kg and 734 kg). Finally, the weight of the tyre with a disc and mounting disc that increased the weight level by 38.30 kg was also counted.

During the measurements, the pulling resistance force of the measuring wheel via an HBM S9M/10kN force sensor with the sampling frequency of 5 Hz was recorded. The measured data were transformed via an HBM Quantum X MX 840A measuring recorder to a personal computer using HBM Catman Easy software which transformed the data to MS Excel in order for them to be used to process the measured results. The speed of the measuring wheel was 0.1 m·s^{-1}.

From the obtained measurements results for the rolling resistance force of the tested tyre, dependencies were created, which are shown in Figure 3, i.e. dependency of the rolling resistance force of the tested tyre on the inflation pressure measured on the concrete surface. In Figure 4, the dependency of the rolling resistance force of the tested tyre on the vertical loading measured on the concrete surface is shown.

From the measurements conducted on the soil: in Figure 5, the dependencies of the rolling resistance force courses on the inflation pressures of the tyre for the vertical loading with 772.30 kg are shown

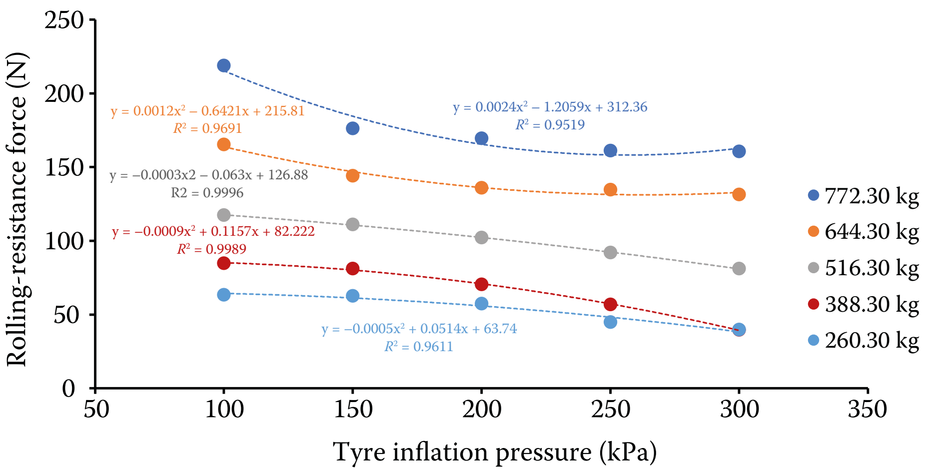

Figure 3. Dependency of the rolling resistance force of the observed tyre on the inflation pressure, concrete surface

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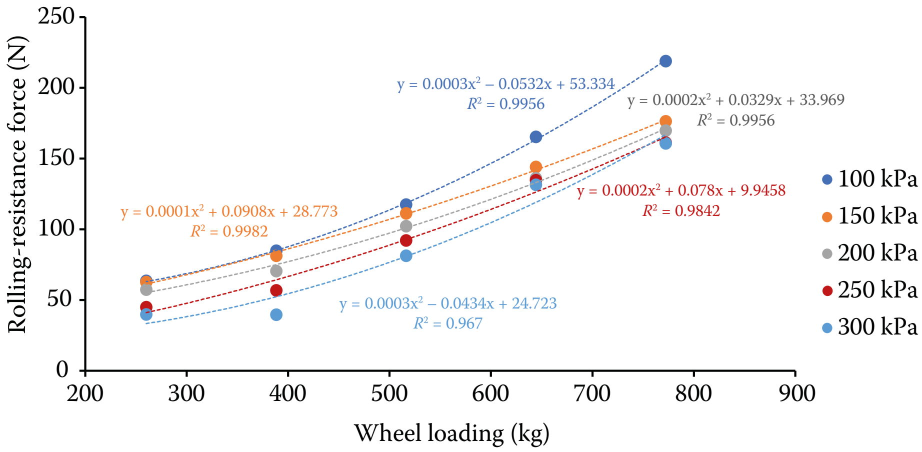

Figure 4. Dependency of the rolling resistance force of the observed tyre on the vertical loading, concrete surface

and, in Figure 6, the dependence of the rolling resistance coefficients on the tyre inflation pressures for the same vertical load level on the tyre.

The measurement process on the concrete surface without the construction of a soil testing canal is verified in Figure 7. The figure represents the carrying frame of the wheel, the used mechanical weights with their positioning, the positioning of the measurement apparatus with a computer and the final disposition of the workplace.

As mentioned above, the monitored tyre was a Mitas TS05 10.0/75-15.3 10PR diagonal tyre. Rolling resistance measurements were performed first on the concrete base of the laboratory (workshop) and then after the installation of the body on the soil channel on the forest soil.

Figure 3 shows the relationship between the achieved rolling resistance and the tyre inflation pressure on a concrete surface. The relationship shows that, with an increasing inflation pressure, the value of the rolling resistance gradually decreases at all the load levels. The reason for this condition is the fact that with an increasing internal pressure in the tyre, there is less deformation of the tyre casing and, thus, a reduction in internal-friction losses (Carvalheira 2012; Arghir and Leu 2013). The main load-bearing element of the tyre is mainly the air with which the tyre is inflated. The higher the pressure, the higher the load capacity of the tyre and the smaller the structural deformation. When we look at Figure 3 again, we can see that an even more significant decrease in the rolling resistance values caused a decrease in the vertical load of the tyre. It is natural that with the lower the load on the tyre, the smaller the structural deformation of the tyre and the smaller the hysteresis losses caused by the deformation are.

We can reach similar conclusions if we look at Figure 4. This represents the dependence of the rolling resistance on the vertical load of the tyre. Here, we also observe that the increasing wheel load clearly increases the value of the rolling resistance (Miege and Popov 2005). On the other hand, the relationship also shows its gradual decrease with an increasing tyre inflation pressure (Rebati and Loghavi 2006).

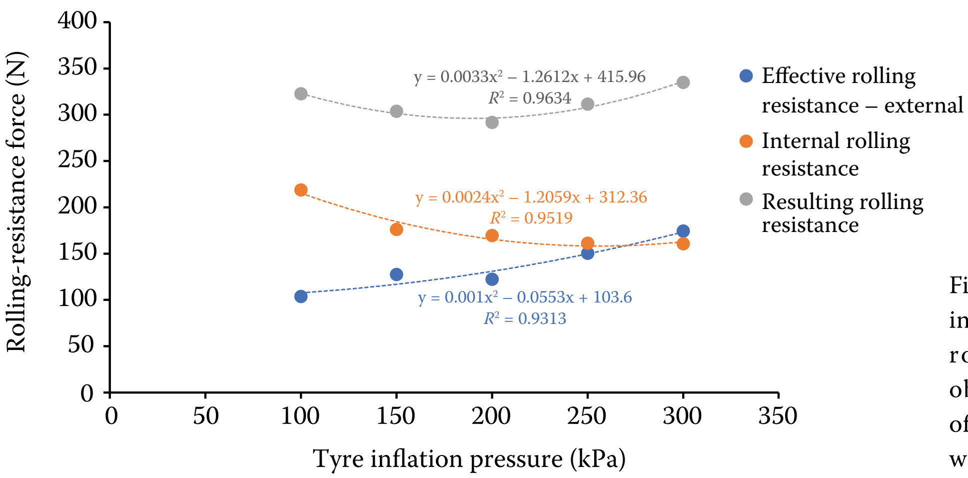

Figure 5. Dependency of the individual parts of the total rolling resistance force obtained by measurement of the tyre's vertical loading with 772.30 kg on the soil

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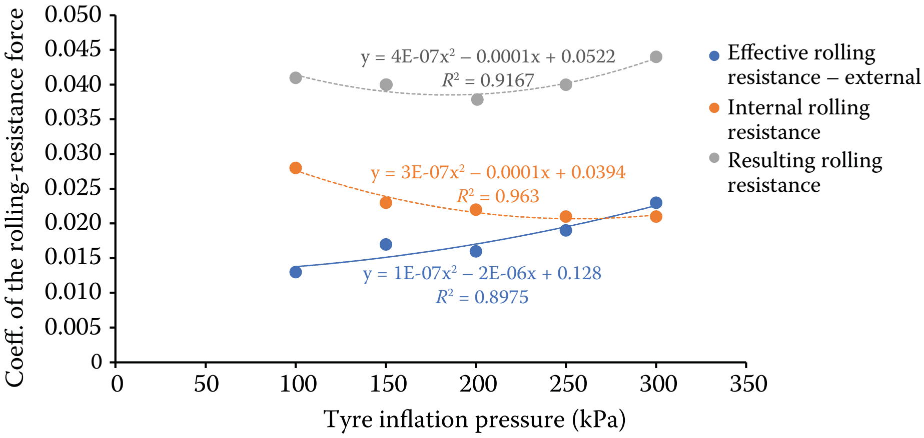

Figure 6. Dependency of the individual parts of the total coefficient of rolling resistance force obtained by measurement of the tyre's vertical loading with 772.30 kg on the soil

coeff. – coefficient (–)

We could justify the causes of this condition in the same way as in the previous Figure 3. In general, we could conclude that the increasing tyre inflation pressure on a rigid surface has a beneficial effect on reducing its rolling resistance. However, increasing this pressure cannot be spontaneous. It is always a compromise between the acceptable rolling resistance values achieved, the load capacity and, last but not least, the service life and reliability of the tyre, while its adhesive properties must not be affected.

Figure 7. Measurement process for the rolling resistance forces

(A) measurement conducted on the concrete surface; (B) measurement conducted on the soil surface in the soil testing canal; (C) positioning of measurement apparatus during the measurements; (D) final layout of the workplace

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The results obtained on the soil show two relationships, namely, as seen in Figure 5, the relationship of the rolling resistance on the tyre inflation pressure at a vertical tyre load of 772.30 kg and, as seen in Figure 6, the relationship of the rolling resistance coefficients on the tyre inflation pressure for the same vertical load. Three curves are plotted in the graphs. One shows the course of the internal component of the rolling resistance of the tyre, the second the course shows the effective value of the rolling resistance, which is related to the deformation of the soil surface, and the third shows the course of the resulting value of the rolling resistance of the tyre.

Both figures essentially lead to the following conclusions. As the tyre inflation pressure increases, the value of the internal component of the rolling resistance of the tyre decreases, which is related to the reduction in the tyre deformation and the reduction in the internal frictional resistances. On the other hand, the value of the external component of the rolling resistance increases, which is due to the increasing mean value of the contact pressure, and, thus, the decreasing contact area and greater soil deformation at a given vertical wheel load (Coutermarsh 2007). With an increasing tyre inflation pressure, the load capacity of the tyre increases and its structural deformation decreases, however, at the same time, the contact area decreases with an increasing stiffness and the mean value of the pressure in the contact area of the tyre increases. Nevertheless, the value of the total rolling resistance has an interesting course, which according to the given graphic dependences, reaches a minimum at the inflation pressure of about 200 kPa. The above course of the achieved rolling resistances, as well as rolling resistance coefficients, indicates that by choosing the right choice of tyre pressure on the soil, we can achieve a certain optimum in terms of reducing the rolling resistances and, thus, effectively reduce the energy intensity of the mechanisation and transport means. This fact, on the other hand, can also have a positive environmental impact, in particular on reducing the damage to productive soils in agriculture and forestry, in particular by compressing them. In this context, however, it should be noted that the given graphical relationships were developed on the basis of a relatively small number of measurements, which may, to some extent, distort the measurement results.

Figure 6, as mentioned above, plots the relationship between the values of the rolling resistance coefficients achieved and the tyre inflation pressure. The rolling resistance coefficient is a good dimensionless coefficient on the basis of which we can compare different kinds, types, and designs of tyres. Here, too, we could draw essentially the same conclusions as in Figure 5.

In Table 2, we present the regression functions which translated the relationships in Figure 5, and Table 3 lists the regression functions that translated the dependences of Figure 6 with the coefficients of determination and correlation coefficients. These relationships were translated by second degree polynomials. The achieved values of the correlation coefficients have values greater than 0.9, on the basis of which we can say that there is a very high tightness of the distribution of measured points around the translated regression function. We achieved similar results in the case of other levels of the vertical load on the monitored tyre.

Table 2. Regression functions of the dependence of rolling resistance on tyre inflation pressure, Figure 5

Dependency	Regression function	Coefficient of determination	Correlation coefficient
Internal rolling resistance	$y = 0.0024x^2 - 1.2059x + 312.36$	$R^2 = 0.9519$	$R = 0.9757$
External rolling resistance	$y = 0.001x^2 - 0.0553x + 103.6$	$R^2 = 0.9313$	$R = 0.9650$
Total rolling resistance	$y = 0.0033x^2 - 1.2612x + 415.96$	$R^2 = 0.9634$	$R = 0.9815$

Table 3. Regression functions of the dependence of rolling resistance coefficients on tyre inflation pressure, Figure 6

Dependency	Regression function	Coefficient of determination	Correlation coefficient
Internal rolling resistance	$y = 3\text{E-}07x^2 - 0.0001x + 0.0394$	$R^2 = 0.9630$	$R = 0.9813$
External rolling resistance	$y = 1\text{E-}07x^2 - 2\text{E-}06x + 0.0128$	$R^2 = 0.8975$	$R = 0.9474$
Total rolling resistance	$y = 4\text{E-}07x^2 - 0.0001x + 0.0522$	$R^2 = 0.9167$	$R = 0.9574$

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CONCLUSION

Two main conclusions that have resulted from the present measurements can be drawn. The first is the fact that, on a rigid surface, it is possible to reduce the rolling resistance of the tyres by increasing their inflation pressure. However, as mentioned above, this increase has its limits essentially due to the trade-off between the rolling resistance achieved and the service life and reliability of the tyre casing, while its adhesive properties should not be affected. The second finding is the fact that, on the soil surface, it is possible to achieve optimal rolling resistance values by the correct choice of tyre inflation pressure and, thus, reduce the overall energy intensity of the wheel mechanisation means, probably also on surfaces of loose and substantially dried materials and soils, as was in our case. Today, there are technical means enabling the regulation of the tyre inflation pressures of the wheel mechanisation means for the operatorin a convenient manner directly from the operator's cab. These devices are generally referred to as CTIS (Central Tyre Inflation System). According to Adams (2002), up to 10% of terrains that have been not passable by conventional wheel technology can be traversed with the right choice of tyre inflation pressures, also thanks to the above technical solution. However, the right choice of tyre inflation pressures not only has its economic and technical justification, but should also lead to a more environmentally friendly impact on the soil environment. An appropriate tyre inflation pressure not only causes a reduction in soil pressure, but also leads to a reduction in tyre slip and, thus, to a reduction in soil texture damage (Helexa and Kováč 2019). In the future, we would like to continue the planned research and try to set the soil in the soil channel to higher moisture values and look for optimal rolling resistance values for the test tyres.

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